RECORD HIGH EFFICIENCY SCREEN-PRINTED BELT CO-FIRED CELLS ON CAST MULTI-CRYSTALLINE SILICON

Ajay Upadhyaya[1], Manav Sheoran[1, 2], Ajeet Rohatgi[1], Keith Matthei[3]
[1]University Center of excellence for Photovoltaic Research and Education, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA.
[2]School of Physics, Georgia Institute of Technology, Atlanta,GA 30332, USA
[3]GT Solar, 243 Daniel Webster Hwy, Merrimack, NH 03054, USA

ABSTRACT: Record-high efficiency screen-printed 4 cm^2 solar cells were achieved on HEM and Baysix cast multi-crystalline silicon. These cells were fabricated using a simple, manufacturable process involving $POCl_3$ diffusion for a 45 Ω/□ emitter, PECVD SiNx:H deposition for a single-layer antireflection coating and rapid co-firing of an Ag grid, an Al back contact, and Al-BSF formation in a belt furnace. This process scheme resulted in effective impurity gettering and defect passivation. It also contributed to good ohmic contacts with series resistance of < 1Ω-cm^2, back surface recombination velocity of < 500 cm^2/s, high average bulk lifetimes in the range of 100-250 µs after cell processing and fill factors of ~0.78. These parameters resulted in record high, 16.9% and 16.8% efficient screen-printed cells on HEM (Heat Exchanger Method) and Baysix mc-Si (confirmed by NREL).The identical process applied to the un-textured Float zone (FZ) wafers gave an efficiency of 17.2%. The optimized co-firing cycle, when applied to HEM mc-Si wafers with starting lifetimes varying over a wide range from 4 - 70 µs, resulted in a very tight efficiency range of 16.6% to 16.8% as a result of efficient defect gettering and passivation. Model calculations performed using the simple cell design and measured cell parameters agreed well with the experimental cell efficiency.
Keywords: multi-crystalline, Solar cell Efficiencies, Lifetime.

1 INTRODUCTION

The mc-Si and ribbon Si currently account for roughly 54% of the PV market. These growth technologies provide silicon substrate at a lower cost. However, these materials suffer from a high density of defects, dislocations, grain boundaries, metallic impurities, and other macro defects compared to their single-crystal counterparts, like Czochralski or Float Zone (FZ) silicon. This is mainly due to the higher impurity content of the silicon feedstock and a high growth/solidification rate, which furthermore prevents the segregation of impurities in the melt. As a result, the minority carrier lifetime in a cast mc-Si ingot is found to be as low as 3-4 µs from certain regions to as high as 60-70 µs. To obtain the high efficiency solar cells with high yield from wafers with such a wide variation in lifetime, it is important to develop a process sequence that can raise the bulk lifetime to a level where it has little effect on cell efficiency.

The commercial cell efficiency for the cast mc-Si lies in the range of 13.5 – 15.0%. Efficiencies as high as 16.6% have been reported on 156 cm^2 cast mc-Si material using a screen-printed, single-layer SiN_x AR coating, isotropic texturing and a selective emitter [1]. In this paper, we report on 4 cm^2 16.9% HEM mc-Si screen-printed, belt co-fired cells with a single-layer SiN_x AR coating. These results were confirmed by National Renewable Energy Laboratory (NREL).These cells do not have any texturing or selective emitter and represent the highest reported screen-printed cell efficiency for this cell design. The 1-2 Ω-cm, ~300 µm thick HEM wafers used in this study were provided by GT Solar.

This paper shows that for a simple n^+-p-p^+ cell design, the screen-printed efficiency of the cast mc-Si cell became comparable to the untextured FZ-Si cells, because of a significant enhancement in bulk lifetime during processing. Equally significant is the finding that the cell efficiency is relatively insensitive to the as-grown lifetime due to effective defect gettering and passivation. This is because once the lifetime exceeds 100 µs for this cell design; the efficiency no longer shows a strong dependence on the bulk lifetime. Performance becomes limited by the cell design, such as emitter and BSF profiles. A combination of gettering and hydrogenation steps used in this study was able to push even the low lifetime wafers above the threshold lifetime, resulting in comparable cell performance. Model calculations were performed using PC1D [2] to establish the threshold lifetime for this cell design, followed by the development of a process to achieve the lifetime in finished cells with efficiencies approaching 17%.

2 EXPERIMENTAL

Solar cells were fabricated by a simple manufacturable process sequence shown in Fig. 1.

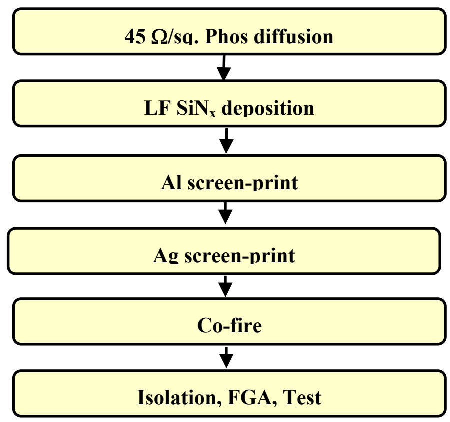
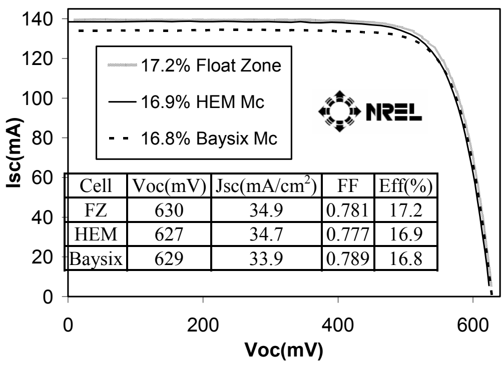


Figure 1: Process sequence used for the fabrication of solar cells reported in this study.

The wafers used in this study were first chemically etched in acid to remove the saw damage and then received a standard RCA clean. Lifetime measurements were taken using the Quasi-Steady-State Photo-conductance (QSSPC) technique [3], with the surface passivated with an iodine-methanol solution [4]. All reported lifetimes were measured at an injection level of 4 x 10^{15} cm^{-3}. The wafers then received $POCl_3$ diffusion to form a ~45 Ω/□ emitter, followed by a SiN_x AR coating on the front, Al screen-printing on the back, and Ag grid printing on the front using commercial pastes. These cells were then co-fired using an optimized process in a lamp-heated IR belt furnace, resulting in simultaneous formation of an Al Back Surface Field (BSF) and the front Ag grid metallization. Finally, cells were annealed at l for 15 min in forming gas before testing and analysis.

3 RESULTS AND DISCUSSION

The average as-grown bulk lifetimes for the HEM mc-Si, Baysix mc-Si and FZ-Si wafers used in this study were ~23 μs, ~42 μs, and >200 μs, respectively. Bulk resistivity of all the wafers was in the range of 1-2 Ω-cm. For the mc-Si cells, V_{oc} values as high as 629 mV were achieved in conjunction with J_{sc} of ~34 mA/cm^2 and a fill factor in the range of 0.78-0.79. FZ Si cells gave a V_{oc} of ~630 mV and J_{sc} of ~35 mA/cm^2. In addition low series resistance (0.6-0.7 Ω-cm^2) and high shunt resistance (≥ 10 Ω-cm^2) values were achieved. Fig. 2 shows the IV curves and the cell parameters for the best cells made on three materials.



Cell	Voc(mV)	Jsc(mA/cm^2)	FF	Eff(%)
FZ	630	34.9	0.781	17.2
HEM	627	34.7	0.777	16.9
Baysix	629	33.9	0.789	16.8

Figure 2: Lighted IV curves and other IV parameters for the mono-Si FZ, HEM, and Baysix mc-Si solar cells, confirmed by NREL.

Nine 2 cm x 2 cm cells fabricated on 10 cm x 10 cm mc-Si wafers often showed very uniform results across the wafer. Fig. 3 shows one of the best efficiency distributions for the nine cells on a Baysix mc-Si wafer with an average efficiency of 16.7% and standard deviation of 0.1%. The average fill factor was 0.789 for these nine cells. This is attributed to uniform printing and firing of the contacts. The average efficiency for the nine cells on a HEM wafer was 16.5%, with the best cell efficiency of 16.9%. It should be noted that 4 cm^2 areas generally include several grains of the multi-crystalline wafer and thus the high efficiencies attained are the result of defect passivation and not selective high lifetime grain.

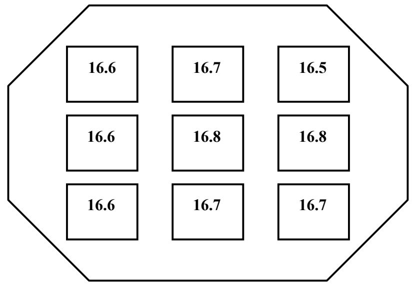


Figure 3: The distribution of the nine 4 cm^2 cells on a 10 cm x 10 cm Baysix mc-Si wafer.

In addition similar results were obtained on these materials in many different runs. Fig. 4 summarizes the efficiency distribution of 150 mc-Si cells fabricated in multiple runs.

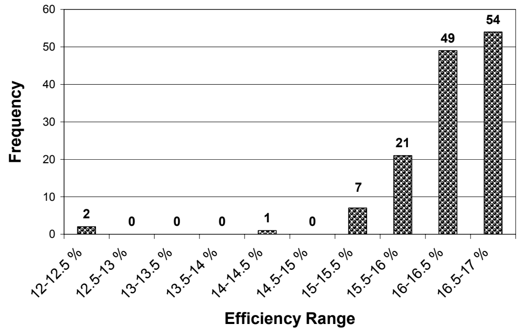


Figure 4: Efficiency distribution of 150 cells on mc-Si in multiple runs.

Spectral response and reflectance measurements were performed on these cells to determine the Internal Quantum Efficiency (IQE). The beam diameter for the spectral response measurement was only a few millimeters. Therefore, the spectral response was measured at four different spots on each 4 cm^2 solar cell. Fig. 5 shows the best IQE response achieved on the highest efficiency Fz, HEM, and Baysix cells. The average weighted reflectance was found to be 11.21 %, 12.11%, and 11.43% for the FZ, HEM and Baysix cells, respectively. Fig. 5 reveals that the HEM cell has an IQE response comparable to the FZ cell in the short wavelength range, whereas in the long wavelength, FZ shows a slightly superior performance. This is attributed to better or uniform BSF quality on single-crystal cells. This was further supported by the effective Back Surface Recombination Velocity (BSRV) values of 350 cm/s for the FZ and 600, 800 cm/s for the HEM and Baysix mc-Si cells. These values were extracted by matching the long wavelength IQE response of the cells in PC1D using the average measured lifetime and the best IQE.

Light Beam Induced Current (LBIC) maps for the FZ and HEM cells are shown in Fig. 6 (a) and (b). Both wafers showed a fairly uniform distribution of high diffusion length regions over most of the cell area. The average LBIC response (amps/watt) for the FZ wafer was 0.546 amps/watt, compared to a 0.542 amps/watt for the HEM cell, supporting the comparable overall cell performance achieved for the HEM and un-textured FZ Si cells.

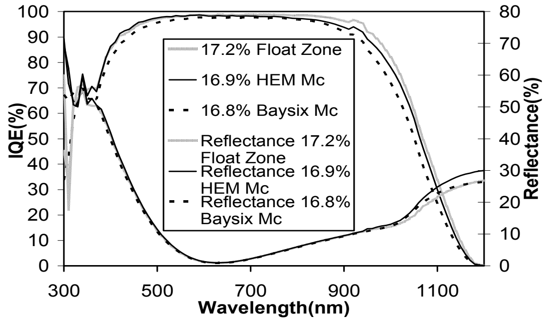


Figure 5: Internal Quantum Efficiency (IQE) and their reflectance curves for the FZ, HEM, and Baysix Si solar cells as a function of wavelength.

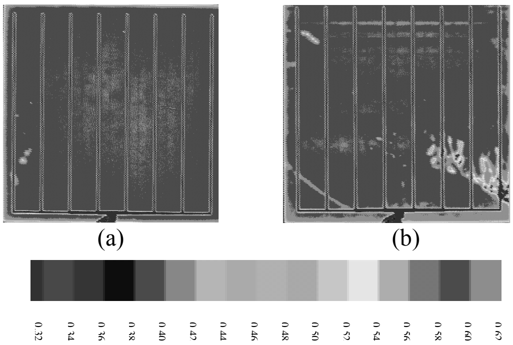


Figure 6: Light Beam Induced Current (LBIC) maps for (a) 17.2% FZ (average response: 0.546 A/W) (b) 16.9% HEM (average response: 0.542 A/W)

The high performance of FZ, HEM, and Baysix Si cells indicate that high-quality BSF, good ohmic contacts, effective $POCl_3$ gettering, and defect passivation via SiN_x-induced hydrogenation were achieved in mc-Si during the belt co-firing of the samples. Since the starting lifetime in all the three cells discussed above was >25 µs, we also investigated mc-Si wafers with an as-grown lifetime in the range of 4-70 µs, using the same optimized fabrication sequence. The relative position of these wafers in the ingot was not known. Solar cells were fabricated on three sets of low (~4 µs), medium (~40 µs) and high (~70 µs) lifetime wafers. Fig. 7 shows the average starting wafer lifetime, average lifetime in the finished cells, and the *average* cell efficiencies obtained from the nine 4 cm^2 cells on each 10 cm x 10 cm wafer (one such set). It is noteworthy that a very small difference in the cell performance (16.6% to 16.8%) was observed despite of a wide variation in the as-grown lifetime (4 to 68 µs). It has been shown that the low lifetime could be the result of impurities or impurity decorated dislocation. However, if the dislocation density is below a certain level (10^4 cm^{-2}) then the impurities can be gettered and defects can be passivated [5]. If the low lifetime is due to high dislocation density > 10^6 cm^{-2}, which is usually the case in the wafers from the top region of mc-Si ingots because of rapid cooling, then the gettering and passivation of the defects in those regions are not as effective [6].

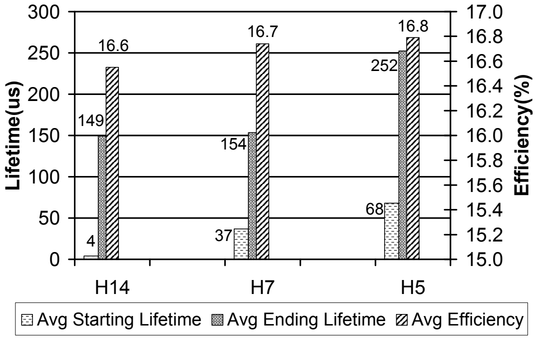


Figure 7: Average as-grown lifetime, average ending (after cell processing) lifetime, and average efficiency for the nine cells for three HEM mc wafers.

The IQE curves for the three mc-Si cells in Fig. 7 are shown in Fig. 8. The long wavelength response of all the three cells is quite comparable. The extracted BSRVs (using PC1D and measured lifetime) for these cells were found to be ~800, ~650, and ~600 cm/s, respectively, for the cells made on the low, medium, and high as-grown lifetime wafers. This is probably because low lifetime wafers also have more defects at the surface, which may interfere with the formation of good and uniform BSF and result in a lower effective BSRV.

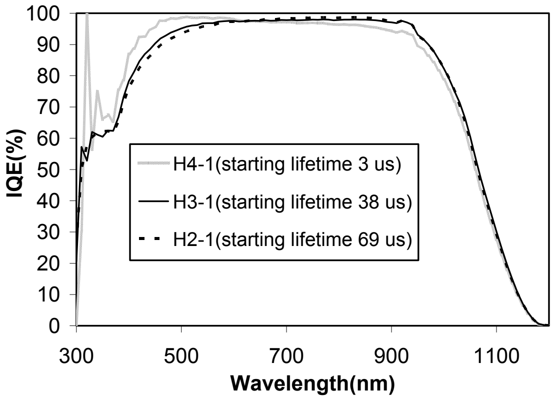
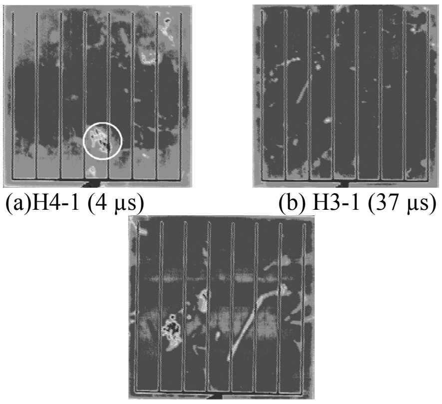


Figure 8: IQE response for HEM mc wafers with different starting (as-grown) lifetimes.

The LBIC response for the same three cells is shown in Fig. 9. The average response (amps/watt) for these cells was consistent with the increasing trend in processed lifetimes. The LBIC map showed some low lifetime regions on the cells. One such spot was chosen on the wafer labeled H4-1 (circled in Fig. 9(a)) and the IQE response was measured. Fig. 9 shows that this region had very low long wavelength response compared to a high LBIC response region, which is indicative of low lifetime and/or low BSRV. There are probably un-passivated defects near the p-p+ interface that could increase the effective back surface recombination velocity.

The three HEM mc-Si cells (Fig. 7) with varying initial lifetimes were etched down to bare silicon to assess the processed lifetime. Processed lifetimes were found to be 149 µs, 154 µs, and 252 µs for the low, medium, and high starting lifetime wafers, with standard deviations of 28 µs, 51 µs, and 74 µs. The processed lifetime distribution over the entire wafer is shown in

Fig. 11 for the high as-grown lifetime wafer. These lifetimes were measured by a QSSPC setup at different locations on the wafer. The QSSPC setup measures lifetimes over a circle that is a few centimeters in diameter, giving an area-averaged number. The significant increase in the processed lifetime is the result of combined effect of $POCl_3$ gettering the SiNx induced hydrogenation, since de-hydrogenation was minimized because of the *rapid* co-fire.


(a)H4-1 (4 µs) (b) H3-1 (37 µs)

(c) H2-1 (68 µs)

Figure 9: Light Beam Induced Current (LBIC) maps for solar cells with different as-grown lifetimes (a) 4 µs, (b) 37 µs, and (c) 68 µs on HEM mc.

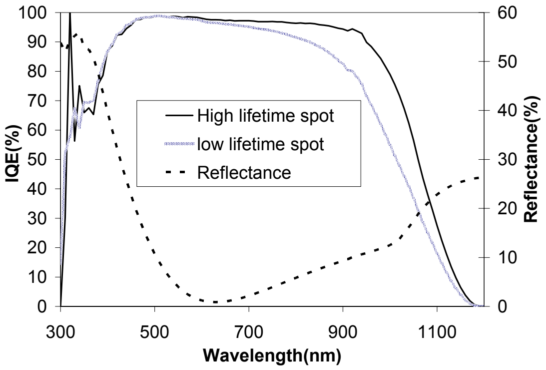


Figure 10: IQE response and the reflectance for a low and high lifetime region of the same cell.

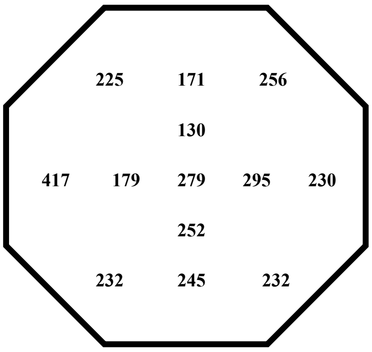


Figure 11: Lifetime distribution after cell processing for a high starting lifetime (68 µs) wafer.

All the wafers, irrespective of their as-grown lifetime, benefited from gettering and hydrogenation. The measured cell parameters such as thickness, emitter profile, reflectance, R_{sh}, R_s, J_{02} etc, were used to perform PC1D calculations. Fig. 12 shows the dependence of efficiency on bulk lifetime for this cell design. Fig. 12 shows that for this cell design efficiency does not change much for the lifetimes above 100 µs. This explains why there was not a significant efficiency gap between the mc-Si cells with a processed lifetime in the range of 100~252 µs (Fig. 7) as well as FZ wafers, with a processed lifetime of > 600 µs. Thus the performance of these cells is primarily being limited by the cell design and technology and not the material quality.

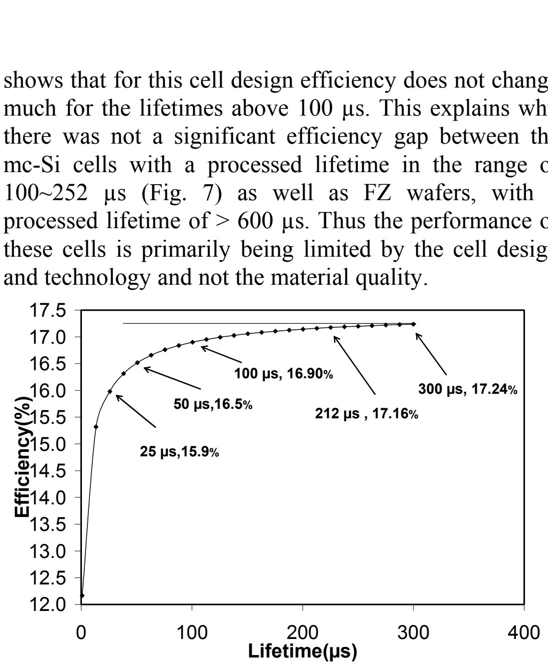


Figure 12: Calculations in PC1D showing the dependence of efficiency on bulk lifetime.

4 CONCLUSIONS

In conclusion, an optimized co-firing process was developed for the fabrication of high-efficiency cast mc-Si solar cells. This resulted in ~17% efficient 4 cm^2 screen-printed solar cells with single-layer AR coating, and no surface texturing or selective emitter. Nine 4 cm^2 cells on a 100 cm^2 Baysix mc-Si wafer showed an average efficiency of 16.7%, with a maximum of 16.8%. The HEM mc-Si wafer gave an average efficiency of 16.5%, with a maximum of 16.9%. These high efficiencies are attributed to the combination of effective gettering and hydrogenation, good ohmic contacts, and effective BSF achieved by this rapid process scheme. It is shown that if the lifetime during processing can be enhanced above a certain threshold (~100 µs for this cell design), the as-grown lifetime becomes relatively inconsequential. We were able to raise the bulk lifetime exceeding 100 µs in the finished cells, even though the starting lifetimes in the cast mc-Si wafers used in this study were in the range of 4 -70 µs. The introduction of surface texturing, a high sheet-resistance emitter, and an improved BSRV can raise these efficiencies to ~18%.

REFERENCES

[1] J. Szlufcik, F. Duerinckx, E. V. Kerschaver, J. Nijs, Proceedings of 17th European Photovoltaic Solar Energy Conference, Munich, Germany, 2001, p. 1271-1276.
[2] P.A. Basore and D. A. Clugston, PC1D V5.6, University of New South Wales, Sydney, Australia (1998)
[3] R. A. Sinton and A. Cuevas, Applied Physics Letters 69(17), 3510(1996)
[4] D. Macdonald and A. Cuevas, Applied Physics Letters 74, 12(1999)
[5] Sopori BL, Jastrzebski L, Tan T, Proceedings of the 25th IEEE photovoltaic Specialists Conference,1994,p 1611.
[6] D. Macdonald, A. Cuevas, F. Ferrazza, Solid State electronics 43 (1999) p 575-581.